A Quantitative Model for the Temperature, Strain Rate, and Grain Size Dependence of Fracture Toughness in Low Alloy Steel

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Prior investigations have established that cleavage fracture initiates in cracked specimens of low alloy steel when the maximum tensile stress level in the plastic zone ahead of the crack, σ_{yy}^{max}, reaches a critical value σ_f^*.(1) This value is known as the microscopic cleavage strength. To build the local stress level up to σ_f^* from the unconstrained value of the tensile yield strength, σ_y, we have proposed(1) that the plastic zone must reach a critical value R_c that is given by

$$R_c = \rho[\exp(\sigma_f^*/\sigma_y - 1) - 1] \tag{1}$$

where ρ is the root radius of the crack.

The plane strain fracture toughness, K_{Ic} (ρ) is that value of stress intensity K at which $R = R_c$.

From sharp crack fracture mechanics, the plane strain plastic zone size is given by(2)

$$R \cong 0.12 \left(\frac{K_I}{\sigma_y}\right)^2$$

so that

$$R_c = 0.12 \left(\frac{K_{Ic}}{\sigma_y}\right)^2 \tag{2}$$

and consequently, for a crack of root radius ρ, equations (1) and (2) give

$$K_{Ic}\ (\rho) = 2.9\ \sigma_y\ [\exp(\sigma_f^*/\sigma_y - 1) - 1]^{1/2} \sqrt{\rho} \tag{3}$$

Figure 1 indicates that the fracture toughness of carbon/manganese steel measured in three point bending at - 196°C does indeed vary with $\sqrt{\rho}$, for $\rho > \rho_o$. For $\rho < \rho_o$ the fracture toughness is the same as that evaluated by standard ASTM specimens which have been notched and fatigue cracked ($\rho=0$) prior to testing. Consequently,

$$K_{Ic} = K_{Ic}(\rho_0) = 2.9\,\sigma_y\,[\exp(\sigma_f^*/\sigma_y-1)-1]^{1/2}\sqrt{\rho_0} \qquad (4)$$

The parameter ρ_0 is known as the "effective root radius" of the crack.$^{(3)}$ It is a measure of the extent of the process zone ahead of the crack over which the ciritical stress σ_f^* must exist to initiate cleavage. It has been proposed$^{(4)}$ that ρ_0 is determined by some microstructural feature, such as grain size or spacing of inclusions or slip or twin bands. If σ_f^* and ρ_0 are independent of temperature, then it is possible to determine the temperature dependence of K_{Ic} and also the dynamic fracture toughness K_{Id} from the temperature and strain rate dependence of σ_y.

Equation (4) predicts that the plane strain cleavage fracture toughness depends only on three parameters, a) σ_f^*, the microscopic cleavage strength, b) σ_y, the yield strength, and c) ρ_0, the effective limiting crack sharpness.

The present research was designed to determine the effect of microstructure and composition on σ_f^*, σ_y, and ρ_0, and therefore determine a direct expression for K_{Ic} in terms of microstructural variables. Small specimens of Charpy dimension (10 x 10 x 60mm.) with 2mm. deep notches of variable radius were used to evaluate K_{Ic} (ρ) and $K_{Ic} = K_{Ic}$ (ρ_0) at -196°C. σ_y was measured separately at the strain rate which exists below the notch during bending. These parameters were then used to determine ρ_0 and σ_f^* from Equation (4).

A low carbon/manganese steel was used for initial investigation. After machining, the specimens were heat-treated to obtain three different grain sizes. This was done by varying the austenitizing temperature and the cooling rate. Three grain sizes $d=1.3\times10^{-3}$ in., 2.5×10^{-3} in., and 3.5×10^{-3} in., were obtained. All specimens then were annealed at 1000°F for three hours to assure the same substructure for the different grain sizes.

The specimens were broken in slow bending at -196°C, and for each case values of K_{Ic} and ρ_0 were determined from Figure 1. The yield strength σ_y was measured separately in a tensile test and Equation (4) was then used to determine σ_f^*. The experimental results on the specimens of varying grain size indicate that:

$$\begin{aligned} &\sigma_y = 44 + 2.7d^{-1/2} && (\dot{\varepsilon} = 8.3\times10^{-3}\ \text{sec}^{-1}.) \\ &\sigma_f^* = 26 + 6.4d^{-1/2} && d^{-1/2} > 11.0 \\ &\rho_0 \cong 3d && \end{aligned} \qquad (5)$$

with σ_y and σ_f^* in units of ksi and d in inches.

Substituting into Equation (4) we get:

$$K_{Ic} = \left(220d^{1/2} + 13.5\right)\left[\exp\left(\frac{3.7d^{-1/2} - 18}{2.7d^{-1/2} + 44}\right) - 1\right]^{1/2} \qquad (6)$$

An instrumented Charpy impact machine was used to duplicate the above results for the dynamic case. Figure 1 shows the results of this work. Dynamic yield strength was determined by extrapolating the general yield load, P_{GY}, measured at higher temperatures down to -196°C and then using the Green and Hundy$^{(5)}$ relation $\sigma_y = 33.3P_{GY}$. It was found that:

$$\begin{aligned} &\sigma_y = 49 + 3.8d^{-1/2} && (\dot{\varepsilon} = 100\ \text{sec}^{-1}) \\ &\sigma_f^* = 26 + 6.4d^{-1/2} && \\ &\rho_0 \cong 3d && \end{aligned} \qquad (7)$$

And substituting in Equation (4) we get:

$$K_{Id} = \left(245d^{1/2} + 19\right)\left[\exp\left(\frac{2.6d^{-1/2} - 24}{3.8d^{-1/2} + 45}\right) - 1\right]^{1/2} \qquad (8)$$

As shown in Figure 2, the experimental values of K_{Ic} and K_{Id} are in excellent agreement with these relations. Equation (6) and (8) predict that for this particular steel subsequent refinement in grain size produces only a slight increase in K_{Ic} and K_{Ic} at -196°C. This fact, which has also been observed for mild steel, arises because although the microscopic cleavage strength σ_f^* is increased by grain refinement, the effective crack tip radius ρ_0 is reduced. The decrease in ρ_0 with decreasing grain size is due to the fact that the stress level should reach σ_f* over a few grains below the notch for cleavage to occur. This distance and therefore, ρ_0, decrease as the grain size is decreased.

Equation (5) and (7) indicate that strain rate has no effect on σ_f* or ρ_0 which indicates that σ_f* and ρ_0 are probably independent of temperatemperature. The decrease in K_{Ic} with increasing strain rate simply results from increasing σ_y with increasing strain rate.

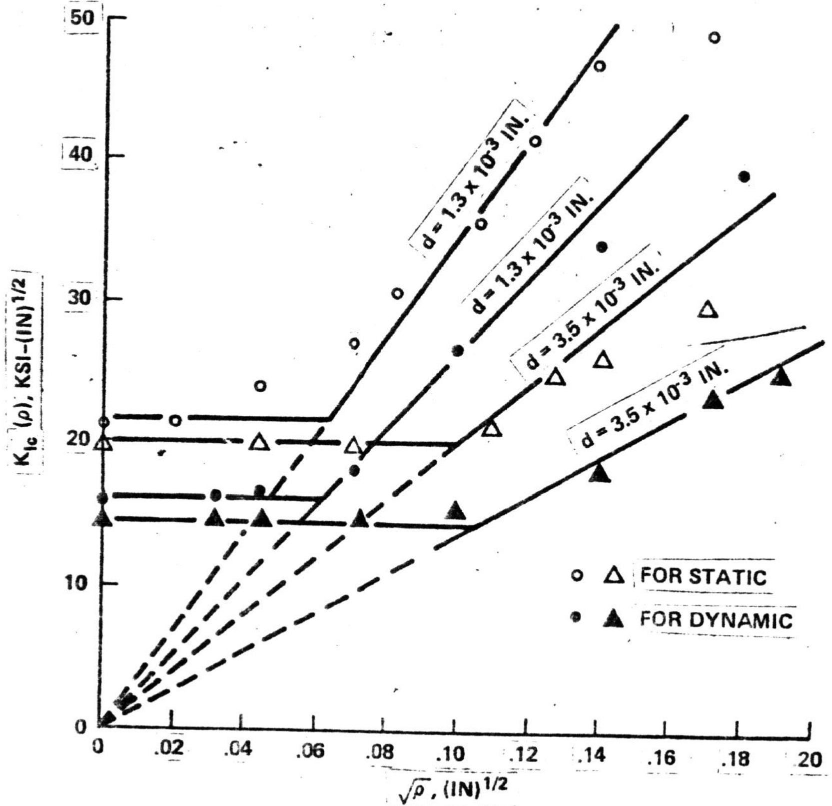

Figure 1. Variation of $K_{Ic}(\rho)$ with Notch Root Radius at -196° C

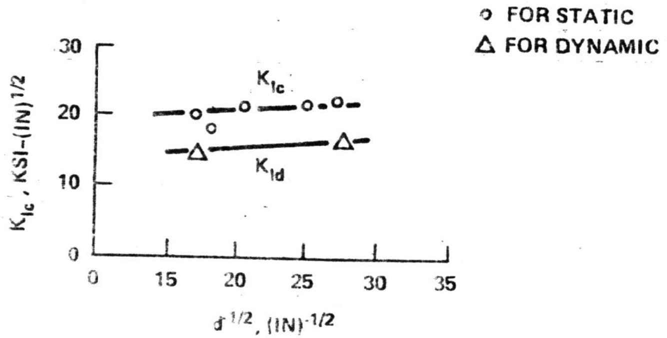

Figure 2. Variation of Fracture Toughness with Grain Size at -196° C

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